

Transit timing variation and activity in the WASP-10 planetary system^{*}

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ABSTRACT

Transit timing analysis may be an effective method of discovering additional bodies in extrasolar systems which harbour transiting exoplanets. The deviations from the Keplerian motion, caused by mutual gravitational interactions between planets, are expected to generate transit timing variations of transiting exoplanets. In 2009 we collected 9 light curves of 8 transits of the exoplanet WASP-10b. Combining these data with published ones, we found that transit timing cannot be explained by a constant period but by a periodic variation. Simplified three-body models which reproduce the observed variations of timing residuals were identified by numerical simulations. We found that the configuration with an additional planet of mass of $\sim 0.1 M_J$ and orbital period of ~ 5.23 d, located close to the outer 5:3 mean motion resonance, is the most likely scenario. If the second planet is a transiter, the estimated flux drop will be ~ 0.3 per cent and can be observable with a ground-based telescope. Moreover, we present evidence that the spots on the stellar surface and rotation of the star affect the radial velocity curve giving rise to spurious eccentricity of the orbit of the first planet. We argue that the orbit of WASP-10b is essentially circular. Using the gyrochronology method, the host star was found to be 270 ± 80 Myr old. This young age can explain the large radius reported for WASP-10b.

Key words: planetary systems – stars: individual: WASP-10.

1 INTRODUCTION

Analysing transit timing variations (TTV) of exoplanets is expected to be an efficient method to discover additional low-mass planets (Miralda-Escudé 2002; Schneider 2004;

Holman & Murray 2005; Agol et al. 2005; Steffen et al. 2007). Many studies have been performed to detect TTV signals but they resulted only in constraints on the parameters of hypothetical second planets (e.g. Gibson et al. 2009). Recently, Maciejewski et al. (2010) detected variation in the transit timing of WASP-3b. They found that a configuration with a hypothetical second planet of mass of $\sim 15 M_{\oplus}$, located close to an outer 2:1 mean motion resonance (MMR) may reproduce the observed TTV signal. Lendl et al. (2010) found some indications for the TTV for OGLE2-TR-L9b but no preliminary solution was proposed.

WASP-10b is an exoplanet discovered by Christian et al. (2009). The mass and radius of the

^{*} Partly based on observations made with the 0.6 and 2.0-m telescopes of the Rozhen National Astronomical Observatory, which is operated by the Institute of Astronomy, Bulgarian Academy of Sciences and the 90-cm telescope of the University Observatory Jena, which is operated by the Astrophysical Institute of the Friedrich Schiller University.
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Table 1. List of telescopes: FoV is the field of view of the instrument and N_{tr} is the number of observed transits.

ID	Telescope	Observatory Location	Detector CCD size	N_{tr} Field of view
1	0.6-m Cassegrain	Astronomical Observatory, N.Copernicus University Piwnice near Toruń, Poland	SBIG STL-1001 1024 × 1024, 24 μm	1 11'8 × 11'8
2	0.6-m Schmidt*	University Observatory Jena, Großschwabhausen near Jena, Germany	CCD-imager STK 2048 × 2048, 13.5 μm	2 52'8 × 52'8
3	0.6-m Cassegrain	National Astronomical Observatory Rozhen, Bulgaria	FLI PL09000 3056 × 3056, 12 μm	4 17'3 × 17'3
4	2-m Ritchey-Chrétien	National Astronomical Observatory Rozhen, Bulgaria	PI VersArray:1300B 1340 × 1300, 20 μm	1 5'8 × 5'6
5	0.8-m Tenagra II	Tenagra Observatories Arizona, USA	SITe 1024 × 1024, 24 μm	1 14'8 × 14'8
6	1.5-m Ritchey-Chrétien	Gunma Astronomical Observatory Takayama, Japan	Andor DW432 1250 × 1152, 24 μm	0** 12'5 × 11'5

* see Mugrauer & Berthold (2010) for details

** no scientific output due to bad weather conditions

planet were found to be $2.96^{+0.22}_{-0.17} M_{\text{J}}$ and $1.28^{+0.08}_{-0.09} R_{\text{J}}$, respectively, larger than interior models of irradiated giant planets predict. The planet orbits its host star in ~ 3.09 d at an orbital semi-major axis of $0.0369^{+0.0012}_{-0.0014}$ au. The eccentricity of the orbit was reported to be $0.059^{+0.014}_{-0.004}$ – a large value for a close-in planet. In the discovery paper Christian et al. (2009) determined transit depth and duration to be 29 mmag and 2.36 h, respectively.

Johnson et al. (2009) and Johnson et al. (2010) re-determined the planet’s parameters with a high-precision light curve using the University of Hawaii 2.2-m telescope with a photometric precision of 4.7×10^{-4} and the mid-transit time error of 7 s. The mass of the planet was found to be $3.15^{+0.13}_{-0.11} M_{\text{J}}$ and the planetary radius turned out to be noticeably smaller, i.e. $1.08 \pm 0.02 R_{\text{J}}$. The latter result was not confirmed by the studies of Krejcová, Budaj & Krushevska (2010) or Dittmann et al. (2010). The first team found the radius of WASP-10b to be in excellent agreement with the value obtained by Christian et al. (2009), and a similar conclusion was reached by Dittmann et al. (2010) with no TTV signature detected.

The host star ($V = 12.7$ mag) is a K5 dwarf with effective temperature of 4675 ± 100 K, located 90 ± 20 pc from the Sun (Christian et al. 2009). Smith et al. (2009) confirmed previous evidences that the light curve of WASP-10 exhibits a rotational photometric variability caused by star spots. The stellar rotation period was found to be 11.91 ± 0.05 d – in agreement with ~ 12 d reported by Christian et al. (2009).

The presence of an additional small planet was suggested to pump the eccentricity of WASP-10b (Christian et al. 2009). This system was therefore a good target for TTV studies.

The order of this paper is as follows. In Section 2 observations and data reduction are summarised. The discovery of the periodic transit timing variation is presented in Section 3. The process of identifying and verifying of the most likely 2-planetary model of the WASP-10 system is described in Section 4. A discussion of the proposed scenario is presented in Section 5. Finally, conclusions are collected in Section 6.

2 OBSERVATIONS AND DATA REDUCTION

We collected 9 light curves of 8 transits of WASP-10b during a dedicated international observing campaign involving telescopes spread worldwide at different longitudes (listed in Table 1 and 2). The transit on July 31, 2009 was observed with two instruments in different observatories. The telescope diameters of 0.6 to 2.0 m allowed us to collect photometric data with 1.1 – 2.7 mmag precision. Observations generally started ~ 1 hour before the expected beginning of a transit and ended ~ 1 hour after the event. However, weather conditions and schedule constraints meant that we were not always able to follow this scheme.

Standard IDL procedures (adapted from DAOPHOT) were used for the reduction of the photometric data collected at the National Astronomical Observatory at Rozhen, Bulgaria, and computing the differential aperture photometry. Using the method of Everett & Howell (2001) several stars (4 to 6) with photometric precision better than 5 mmag were selected to create an artificial standard star used for differential photometry. Data from the remaining telescopes were reduced with the software pipeline developed for the Semi-Automatic Variability Search sky survey (Niedzielski, Maciejewski & Czar 2003). To generate an artificial comparison star, 30–50 per cent of the stars with the lowest light-curve scatter were selected iteratively from the field stars brighter than 3 mag below the saturation level. To measure instrumental magnitudes, various aperture radii were used. The aperture which was found to produce light curves with the smallest scatter was used to generate a final light curve.

3 RESULTS

3.1 Light curve analysis

A model-fitting algorithm available via the Exoplanet Transit Database (Poddany, Brát & Pejcha 2010) was used to derive transit parameters: duration, depth and mid-transit time. The procedure employs the OCCULTSMALL routine of Mandel & Agol (2002) and the Levenberg–Marquardt non-linear least squares fitting algorithm which also provides uncertainties. As our research was focused on determining

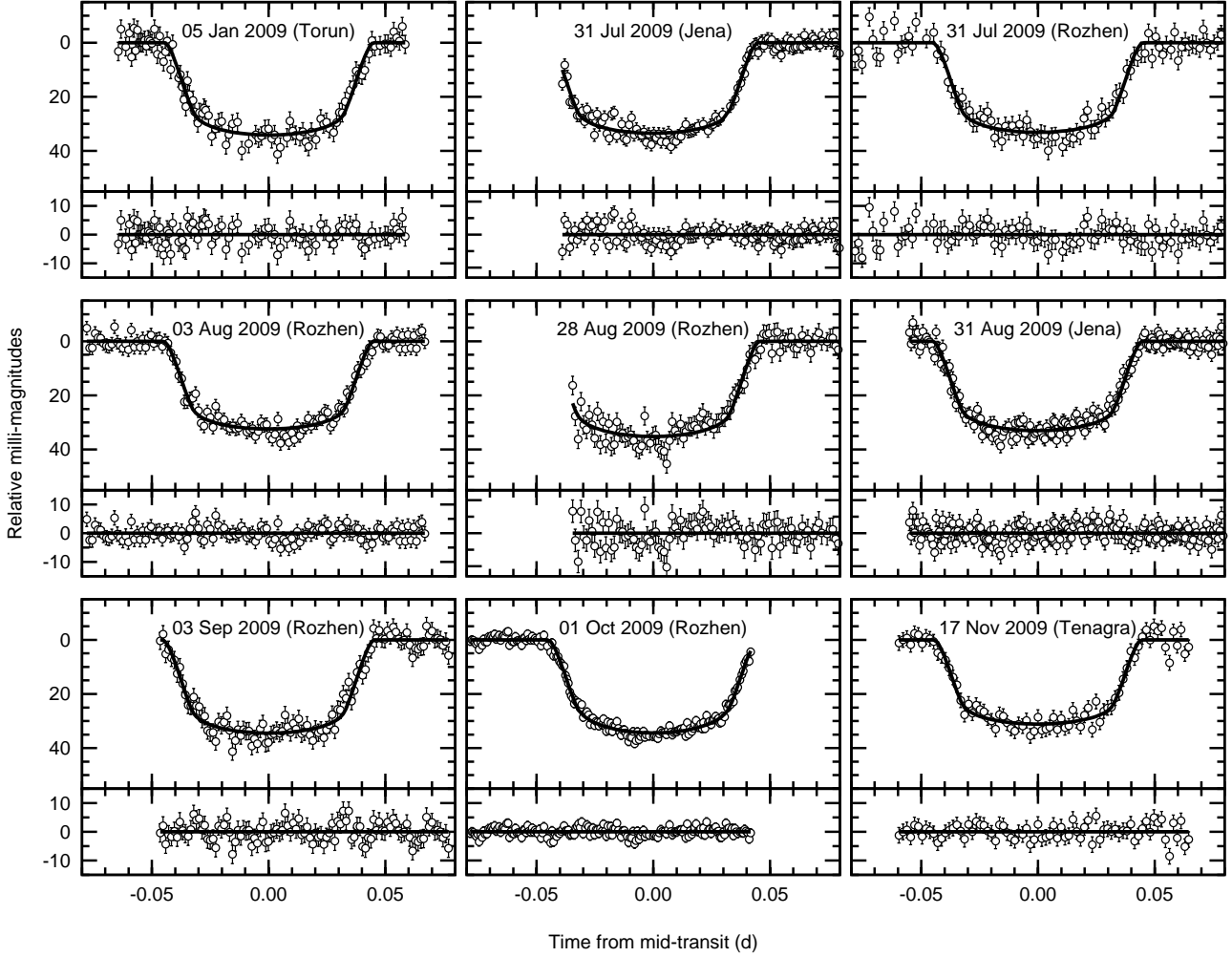


Figure 1. Light curves of WASP-10b transits in individual runs. The best-fitting models are shown as continuous lines. The transit on 31 July was observed simultaneously by two observatories.

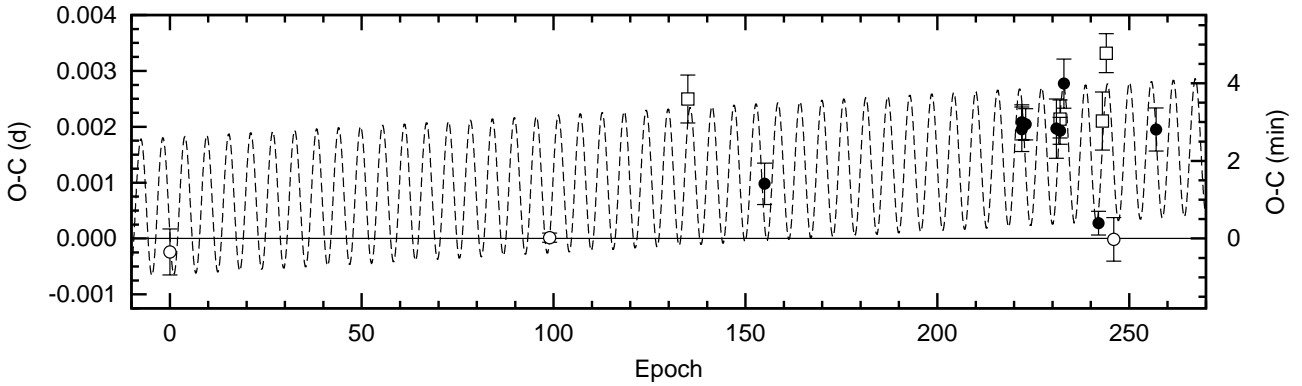


Figure 2. The observation minus calculation ($O - C$) diagram for WASP-10b generated for linear ephemeris based on literature data (continuous line). Open circles denote literature data taken from Christian et al. (2009), Johnson et al. (2010) and Dittmann et al. (2010). Open squares are based on reanalysed photometry from Krejcová et al. (2010). Filled symbols denote results from our campaign. A significantly better fit may be obtained for the new ephemeris given by Eq. 1 (dashed line). 3σ error bars were taken for mid-transit time reported by Dittmann et al. (2010). Their light curve was not corrected for a linear trend which is well visible in out-of-transit phases (J. Dittmann 2010, priv. comm.). Our tests showed that this effect significantly affected the accuracy of the mid-transit time.

Table 2. The summary of observing runs: ID – the identification of the instrument according to Table 1, N_{exp} – number of useful exposures, T_{exp} – exposure times. Dates UT are given for the beginning of nights.

Run	Date	ID	Filter	N_{exp}	T_{exp} (s)
1	2009 Jan. 5	1	<i>R</i>	254	50
2	2009 July 31	2	<i>R</i>	144	60, 80
3	2009 July 31	3	<i>R</i>	116	120
4	2009 Aug. 3	3	<i>R</i>	122	90
5	2009 Aug. 28	3	<i>R</i>	99	90
6	2009 Aug. 31	2	<i>R</i>	203	50, 60
7	2009 Sep. 3	3	<i>R</i>	105	90
8	2009 Oct. 1	4	<i>V</i>	548	15
9	2009 Nov. 17	5	<i>R</i>	76	90

mid-transit times, the number of parameters to be fitted could be reduced. An impact parameter $b = a \cos i / R_* = 0.299^{+0.029}_{-0.043}$, where a is semi-major axis, i is inclination and R_* is host-star radius, was taken from Johnson et al. (2009) and was fixed during the fitting procedure. We used the linear limb-darkening law by Van Hamme (1993) with the limb-darkening coefficient linearly interpolated for the host star in a given filter. A first- or second-order polynomial was used to remove trends in magnitude or flux. The mid-transit times were corrected from UTC to Terrestrial Dynamical Time (TT) and then transformed into BJD (Eastman, Siverd & Gaudi 2010). Light curves with best-fitting models and residuals are shown in Fig. 1 and derived parameters are collected in Table 3.

Krejcová et al. (2010) also published observations and *R*-band light curves of four complete transit events of WASP-10b. In their analysis they focussed mainly on the determination of the planet radius and did not study the mid-transit times, $O - C$ diagram or TTV. We determine 4 mid-transit times for these observations and placed them into the context of our data to create a larger sample for TTV analysis. We used the same method to determine the mid-transit times from their light curves as for all other observations presented here. Corresponding, mid-transit times are presented in Table 3.

Across all data sets, two transits on epochs 222 and 232 were observed simultaneously by two different telescopes. The data were reduced with different pipelines and by different teams. The transit on epoch 222 was observed with 60-cm telescopes in Jena and at Rozhen. The difference in mid-transit times was found to be ~ 11 s. The transit on epoch 232 was covered by observations in Jena and the 50-cm telescope in Stará Lesná in Slovakia (Krejcová et al. 2010). In this case the discrepancy of timing was found to be ~ 18 s. Timing differences are well within error bars of individual determinations for both transits. This practical test strengthens the reliability of our mid-transit time determinations.

3.2 Detection of a TTV

While determining new linear ephemeris, we noted that a linear fit of the epoch E and orbital period P_b of WASP-10b resulted in reduced $\chi^2_{\text{red}} = 13.8$. Individual mid-transit errors were taken as weights in the fitting procedure. Such

a high value of χ^2_{red} suggests the existence of additional signal in the $O - C$ diagram (Fig. 2). The Lomb–Scargle periodogram (Lomb 1976; Scargle 1982) of the residuals revealed the existence of 2 peaks of similar significance and frequencies of 0.175 and 0.183 $\text{cycl } P_b^{-1}$ (Fig. 3). For each frequency, an ephemeris was refitted with the linear trend plus a sinusoidal variation in the form:

$$T_b = T_0 + E \times P_b + A_{\text{ttv}} \sin \left(2\pi \frac{E - E_{\text{ttv}}}{P_{\text{ttv}}} \right) \quad (1)$$

where T_0 is the mid-transit time for initial epoch ($E = 0$), A_{ttv} is the semi-amplitude of detected transit timing variation, E_{ttv} is the epoch offset of the TTV signal and P_{ttv} is its period. The minimal $\chi^2_{\text{red}} = 3.2$ was obtained for $f_1^{\text{ttv}} = 0.183 \text{ cycl } P_b^{-1}$ and resulted in $T_0 = 2454357.86011 \pm 0.00047$ BJD_{TT}, $P_b = 3.0927183 \pm 0.0000021$ d, $A_{\text{ttv}} = 0.00120 \pm 0.00036$ d, $E_{\text{ttv}} = 1.8 \pm 0.4$ and $P_1^{\text{ttv}} = 5.473 \pm 0.012 P_b$.

The procedure run for $f_2^{\text{ttv}} = 0.175 \text{ cycl } P_b^{-1}$ gave $\chi^2_{\text{red}} = 4.1$, $P_2^{\text{ttv}} = 5.7172 \pm 0.0082 P_b$ and similar values of T_0 and P_b . In this case the fit turned out to be poorer, thus we used the ephemeris based on parameters obtained for P_1^{ttv} .

The ephemeris calculated according to Eq. 1 (and P_1^{ttv}) is plotted in Fig. 2 with a dashed line. The $O - C$ values which are used in further analysis were calculated according to the linear part of Eq. 1.

To check if a random distribution of data points in the $O - C$ diagram may favour the detected frequencies, 10^5 fake data sets were generated. The original residuals were replaced with random values with a white-noise distribution of the amplitude. Then, the Lomb–Scargle algorithm was run to find a dominant frequency in each fake diagram. The histogram of these frequencies, with the number of bins equal to the square root of the number of data points in the sample, is presented in Fig. 4. Detected TTV frequencies, f_1^{ttv} and f_2^{ttv} , are not associated with any significant peak in the histogram.

Kipping & Bakos (2010a) pointed out that the transit phasing which is the time difference between the expected mid-transit moment and the nearest data point in a light curve may generate a spurious TTV signal. For example, for a light curve of 60-s cadence time difference is expected to be ± 30 s (Kipping & Bakos 2010b). Cadences of our individual light curves are in a wide range between 19 and 143 s (see Table 3) with the median value of 63 s. This value is ~ 3 times smaller than the amplitude of the detected TTV signal. As it is shown in Fig. 5, no correlation between individual residuals and cadences was detected. A formal least-square fit to this data set resulted in the correlation coefficient $R = -0.36$ which clearly reveals no correlation at the relevant level. The checks discussed above strengthen the detection of the TTV signal in our data set.

4 TWO-PLANETARY MODEL

The possible non-zero eccentricity postulated by Christian et al. (2009) might potentially have resulted from confusion with a two-planet system in which both planets orbit their host star in circular orbits in an inner 2:1 resonance (Anglada–Escude et al. 2010). Although we argue later that eccentricity of WASP-10b is indistinguishable from zero, the case of an inner perturber was considered

Table 3. Parameters of transit light-curve modelling. T_0 denotes the mid-transit time, T_d – transit time duration, δ – depth, σ – averaged standard deviation of the fit and E – epoch. $O - C$ values were calculated according to the linear part of Eq. 1 and the best-fitting parameters. $O - C$ values are given both in days and in units of multiples of the uncertainty of the mid-transit times. t_{cad} is the mean cadence of a light curve. Results of reanalysed data from Krejcová et al. (2010) are collected below the horizontal line. BJD times are based on Terrestrial Dynamical Time (TT).

Run	T_0 BJD _{TT} – 2450000	T_d (min)	δ (mmag)	σ (mmag)	E	$O - C$ (d)	$O - C$ (T_0 errors)	t_{cad} (s)
1	4837.23116 ± 0.00037	128.9 ± 1.4	34.1 ± 0.8	2.7	155	−0.00030	−0.8	56
2	5044.44427 ± 0.00032	128.9 ± 1.2	33.5 ± 1.1	1.7	222	+0.00069	+2.2	87
3	5044.44415 ± 0.00040	129.1 ± 1.5	33.1 ± 0.7	2.6	222	+0.00057	+1.4	130
4	5047.53696 ± 0.00028	129.4 ± 1.0	32.4 ± 0.5	2.0	223	+0.00066	+2.3	103
5	5072.27861 ± 0.00053	131.1 ± 2.1	35.2 ± 0.8	2.5	231	+0.00056	+1.1	102
6	5075.37129 ± 0.00024	129.2 ± 0.8	33.0 ± 0.7	2.0	232	+0.00053	+2.2	63
7	5078.46485 ± 0.00044	130.4 ± 1.5	34.5 ± 1.1	2.5	233	+0.00137	+3.1	102
8	5106.29681 ± 0.00021	129.8 ± 0.7	34.4 ± 0.7	1.1	242	−0.00115	−5.4	19
9	5152.68923 ± 0.00039	128.8 ± 1.3	33.3 ± 2.4	2.1	257	+0.00051	+1.3	143
					135	+0.00125	+2.9	35
					232	+0.00073	+2.2	26
					243	+0.00068	+1.3	36
					244	+0.00189	+5.4	36

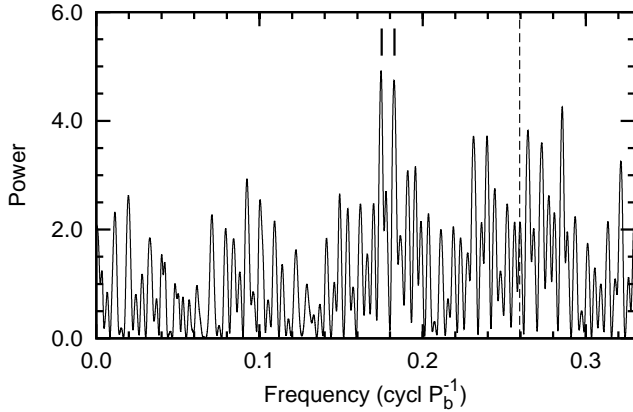


Figure 3. The Lomb–Scargle periodogram generated for timing residuals plotted in Fig. 2, showing the existence of a periodic signal. The most significant peaks are indicated. The upper limit of the periodogram is determined by the Nyquist frequency for the data set. The vertical dashed line marks the rotational period of the host star (see Section 5).

for completeness of our analysis¹. Assuming circular orbits, the mass of the perturbing planet M_c depends on the mass of the outer, more massive transiting planet M_b and its apparent eccentricity e_b (Anglada–Escude et al. 2010). This results in $M_c \approx 0.14 M_J$ in the WASP-10 system. Such a planet is expected to produce strong gravitational perturbations which should be visible as the TTV of WASP-10b. To check this scenario, we generated synthetic $O - C$ diagrams for WASP-10b in systems with a second planet. Parameters of the transiting planet and its host star were taken from Johnson et al. (2009). Initial circular and coplanar orbits were assumed for both planets. The perturbing planet was put in an orbit with the semi-major

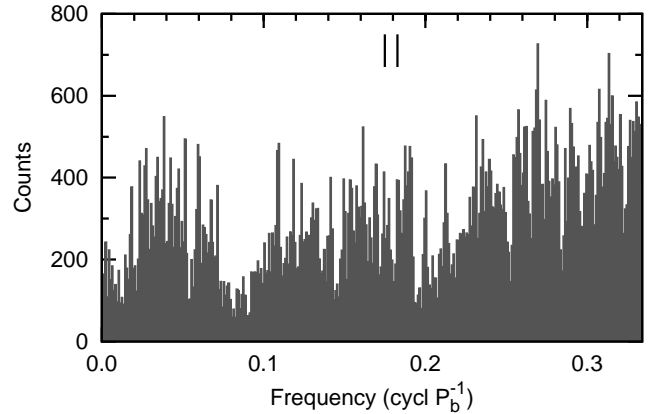


Figure 4. The distribution of dominant frequencies for 10^5 fake $O - C$ diagrams with observed data points replaced by the white noise. The number of bins is equal to the square root of the number of data points in the sample and the width of individual bins is $0.001 \text{ cycl } P_b^{-1}$. Detected TTV frequencies, f_1^{ttv} and f_2^{ttv} , are indicated. No significant peak is associated with any of them what indicates that a spectral window is not a source of detected periodicities.

axis between 0.0218 and 0.0257 au (± 0.0020 au away from the 2:1 orbital resonance). Calculations were performed using the MERCURY package (Chambers 1999) employing the Bulirsch–Stoer integrator. Simulations covered 270 periods of WASP-10b, i.e. the time span covered by observations. No configuration was found to reproduce periodicity close to P_1^{ttv} and P_2^{ttv} . The procedure was repeated for inner 3:1 and 3:2 MMRs but these cases also brought negative results.

To search for configurations with an outer perturber reproducing P_1^{ttv} and P_2^{ttv} , synthetic $O - C$ diagrams were generated with the PTMET code which is based on perturbation theory (Nesvorný & Morbidelli 2008; Nesvorný 2009). Both planets were put in initial circular orbits. The semi-major axis a_c of the perturber varied between 0.0500 and 0.3000 au

¹ We do not analyse the scenario with an exomoon orbiting WASP-10b because no transit duration variation, predicted by Kipping (2009), was detected in our data.

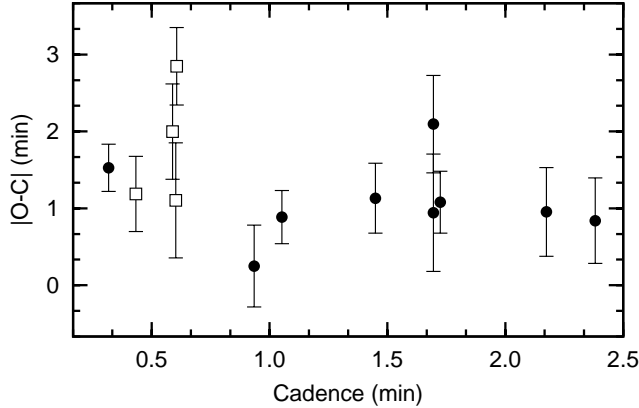


Figure 5. Absolute values of individual residuals in transit timing vs. cadence. Symbols denote the same data sets as in Fig. 2. No correlation between both quantities was found.

Table 4. Outer-perturber solutions which reproduce the observed $O - C$ variation. P^{ttv} indicates which periodicity in the $O - C$ diagram (P_1^{ttv} or P_2^{ttv}) is reproduced by a solution, a_c denotes the semi-major axis of the perturbing planet, M_c is its mass, P_c is its orbital period, K_c is the expected semi-amplitude of the radial-velocity variation and χ_{red}^2 is the lowest value of reduced chi-square for direct model fitting.

No.	P^{ttv}	a_c (au)	M_c (M_J)	P_c (d)	K_c (m s^{-1})	χ_{red}^2
1	1	0.0536	0.10	5.2293	14.2	1.5
2	2	0.0539	0.10	5.2647	14.1	2.5
3	2	0.0682	0.55	7.4962	69.1	2.8
4	1	0.0686	0.55	7.5677	68.9	2.8

in steps of 0.0001 and 0.0002 au for $a_c \leq 0.1$ and $a_c > 0.1$ au, respectively. The amplitude of the TTV signal scales nearly linearly with the perturber’s mass (Nesvorný & Morbidelli 2008), thus M_c was fixed and set equal to $0.3 M_J$ for the preliminary identification. Each simulation covered 270 periods of WASP-10b. Periodic signals reproducing P_1^{ttv} and P_2^{ttv} were identified close to 5:3 and 5:2 MMRs for perturber masses of ~ 0.1 and $\sim 0.5 M_J$, respectively.

To refine parameters of a perturbing body, the synthetic $O - C$ diagrams were calculated with the MERCURY code and the Bulirsch-Stoer integrator. The initial parameters of planet c were taken from previous simulations and then refined with the mass varying in steps of $0.05 M_J$. Each simulation covered 31000 days (i.e. ~ 10000 periods of WASP-10b). The synthetic $O - C$ diagrams were directly fitted to observed data by shifting along the time axis and adjusting to the time span covered by observations. The best-fitting solutions are collected in Table 4. The chi-square test favours solution 1 which reproduces P_1^{ttv} with minimal $\chi_{\text{red}}^2 = 1.5$. This value is significantly smaller than χ_{red}^2 obtained in an analogous way for remaining configurations. The $O - C$ diagram with solution 1 is presented in Fig. 6 where the residuals are also plotted.

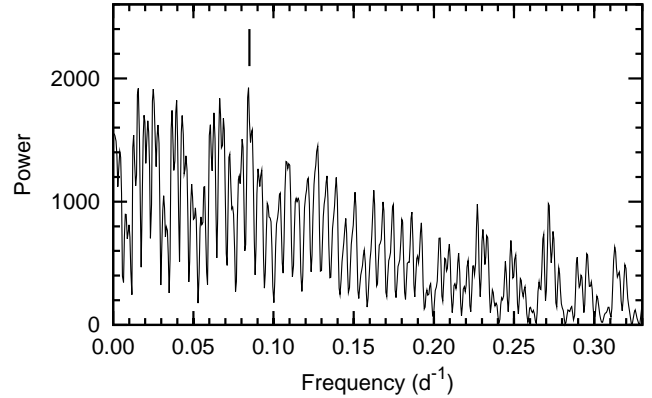


Figure 7. The Lomb–Scargle periodogram for the radial velocity residuals after removing the transiting planet in a circular orbit. A peak corresponding to the stellar rotation is marked.

5 SPECTROSCOPIC REANALYSIS AND STELLAR ACTIVITY

To re-assess the possible solutions, we reanalysed radial velocity (RV) data published by Christian et al. (2009). We used the SYSTEMIC CONSOLE software (Meschiari et al. 2009). The host star is known to be variable due to stellar rotation and starspots (Smith et al. 2009). It was shown that this effect may generate the RV variations up to a few hundred m s^{-1} (Hatzes 2002) and mimic a planetary companion on a Keplerian orbit (Desort et al. 2007). We reanalysed RV data assuming WASP-10b has a circular orbit. This resulted in a best-fitting model with $\chi_{\text{red}}^2 = 3.9$ and $rms = 49.6 \text{ m s}^{-1}$. The periodogram of the residuals (Fig. 7) reveals a periodicity of $\sim 11.84 \text{ d}$ – a value close to the period of stellar rotation $P_{\text{rot}} = 11.91 \pm 0.05 \text{ d}$ determined by Smith et al. (2009). The fitting procedure was repeated with an additional sinusoid signal of period P_{rot} and a floating phase and amplitude. The eccentricity of WASP-10b, e_b , was also allowed to vary. This resulted in a significantly improved model with $\chi_{\text{red}}^2 = 2.5$ and $rms = 31.4 \text{ m s}^{-1}$. The eccentricity was found to be $e_b = 0.013 \pm 0.063$ and it is statistically indistinguishable from zero. Therefore, we adopted $e_b = 0.0$ in further analysis. This result is not surprising as tidal interactions with the host star are expected to circularise the orbit of the planet (Zahn 1977).

To check if the perturbing planet may be hidden in the RV residuals of the model composed of the planet b and starspots, the second planet with physical and orbital parameters as in solutions 1–4 was put into the system. A circular Keplerian orbit of the second planet and coplanarity were assumed for simplicity. We noted that only solutions 1 and 2 significantly decrease the rms of the RV model to 24.7 and 22.5 m s^{-1} , respectively. Combining results of the TTV and RV analysis, we found solution 1 the most likely. The RV curves are plotted in Fig. 8 for individual components, i.e. WASP-10b, WASP-10c and the starspots effect.

The RV semi-amplitude generated by stellar rotation was found to be $\sim 65 \text{ m s}^{-1}$. RV observations by Christian et al. (2009) span from August 2007 to February 2008 and are partially covered by photometric observations from the SuperWASP survey (Pollacco et al. 2006). Smith et al. (2009) determined the amplitude of photomet-

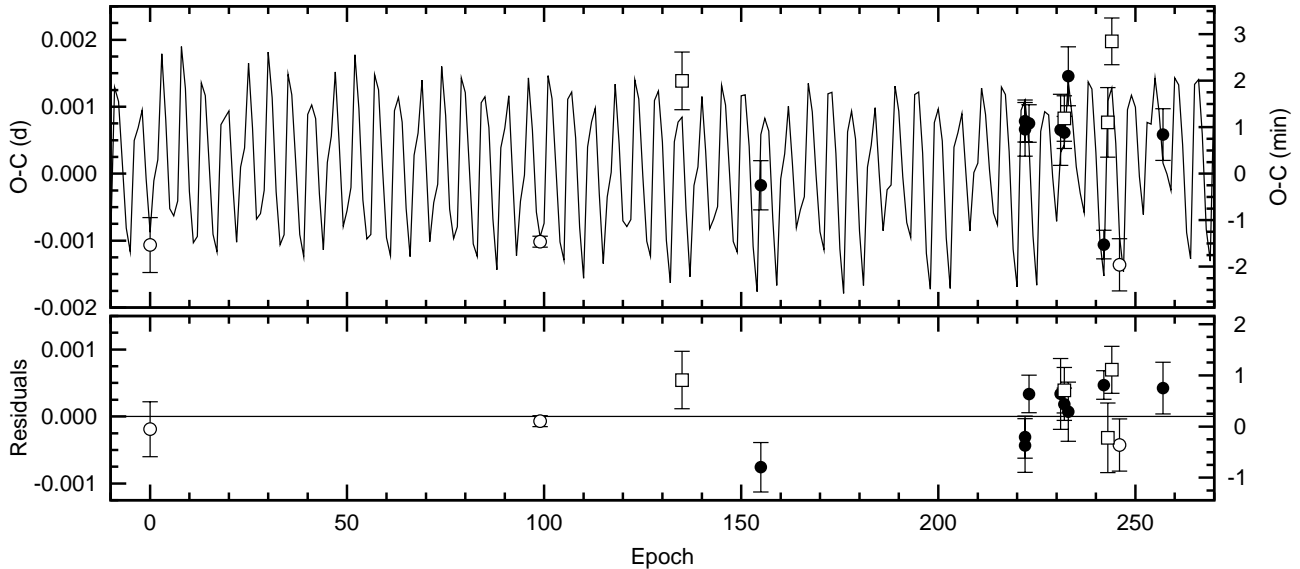


Figure 6. The $O - C$ diagram for WASP-10b with the best-fitting model (solution 1 in Table 4). The mass of the perturber is $0.10 M_J$ and its orbital period is ~ 5.23 d. Symbols are the same as in Fig. 2. Residuals are plotted in the bottom panel.

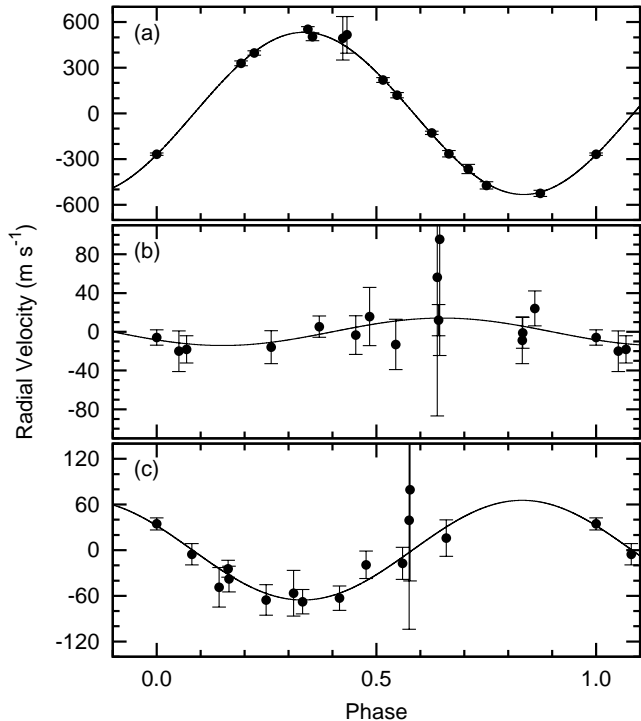


Figure 8. Radial-velocity curves after removing remaining 2 components for a) WASP-10b, b) WASP-10c and c) starspots effect. Data were taken from Christian et al. (2009). Two points with large error bars were obtained in poor weather conditions and may exhibit systematic errors due to scattered moonlight (see e.g. Latham et al. 2010).

ric variation in the 2004 and 2006 seasons only. To find this variation in the 2007 season and verify determinations from Smith et al. (2009), the analysis of variance method (ANOVA, Schwarzenberg-Czerny 1996) was applied to the WASP-10 light curve divided into individual seasons. A peri-

odic signal was identified. Then, a sinusoid was fitted to the phased light curve to determine the amplitude. We determined peak-to-peak amplitudes of 20.8 ± 1.3 , 10.4 ± 1.0 and 8.5 ± 0.9 mmag for the 2004, 2006 and 2007 seasons, respectively. Our values are similar to the results of Smith et al. (2009) who reported 20.2 and 12.6 mmag for 2004 and 2006, respectively. Desort et al. (2007) showed that for a G2V-type star with $v \sin i = 7 \text{ km s}^{-1}$ and a photometric amplitude of 1 per cent (parameters close to those of WASP-10), a spot may produce RV variations with the semi-amplitude of $\sim 70 \text{ m s}^{-1}$. This estimation is consistent with the value determined by us from the RV model analysis.

Stellar spots may affect the transit depth (e.g. Czesla et al. 2009). We found in our data that transit depth variation is smaller than the level of 3σ for individual transits which is thus insignificant. If stellar spots are located along a planet's path projected onto a stellar disk, the shape of the transit may be deformed. This effect may have an influence on determining mid-transit times and result in a spurious periodic TTV signal (e.g. Alonso et al. 2009). Visual inspection of photometric residuals (Fig. 1) does not reveal features which could be related to stellar inhomogeneities rather than to red noise. In particular, there are no deviations visible in light-curve residuals during ingress or egress. Such deformations caused by occulting spots located close to a limb of the stellar disk are expected to generate significant TTV amplitude, even greater than a minute (Miller-Ricci et al. 2008b). Furthermore, no peak close to the rotational period of the star was found in the periodogram of the $O - C$ diagram (Fig. 3) and f_1^{ttv} is not an alias of the rotational frequency of the host star (Alonso et al. 2009).

The proposed model of the WASP-10 system (solution 1) was found to be dynamically stable. Simulations were performed with the SYSTEMIC CONSOLE employing Bulirsch-Stoer integrator and covered 10^6 yr with a maximal time step of 10^{-4} yr. The eccentricity of WASP-10b was found

to be close to zero, while eccentricity of WASP-10c did not exceed 0.05 with a median value of 0.024.

6 AGE OF THE SYSTEM

Given the relatively short rotation period of ~ 12 days of WASP-10, gyrochronology (Barnes 2007) can roughly yield the age of the star: For a K5 dwarf with $(B - V) = 1.15$ mag (Schmidt-Kaler 1982), we get 270 ± 80 Myr only, suggesting that the star (and the planetary system) is quite young. Christian et al. (2009) estimated the rotational age to be between 600 Myr and 1 Gyr by comparing the spin period of WASP-10 to stars in Hyades (Terndrup et al. 2000). However, one must note that according to Fig. 7 and 8 in Terndrup et al. (2000), there are also Pleiades members of spectral type around K5 (like WASP-10) with $v \sin i$ around 6 km/s or lower (as WASP-10, Christian et al. 2009). This method shows that Pleiades-like young age or an age intermediate between Pleiades and Hyades is possible for WASP-10.

To confirm the relative young age of WASP-10, we investigated its kinematic properties. The proper motion of WASP-10 is $(\mu_\alpha \cos \delta, \mu_\delta) = (21.4 \pm 2.0, -28.9 \pm 1.0)$ mas yr $^{-1}$ (Zacharias et al. 2003) and its radial velocity is -11.44 ± 0.03 km s $^{-1}$ (Christian et al. 2009) yielding a heliocentric velocity of $(U, V, W) = (-0.3 \pm 0.9, -17.3 \pm 1.7, -8.1 \pm 3.2)$ km s $^{-1}$. First, we compared the stars's spatial velocity with these of known nearby moving groups including the Pleiades and Hyades (Antoja et al. 2008, e.g. their Figure 5, Table 3; Zhao et al. 2009, e.g. their Figure 2, Table 1). We found that WASP-10 cannot be associated with any of the moving groups. In fact, it lies in an area in the U - V plane where the star density is rather low, which may indicate that this star was either formed in isolation (very rare) or was ejected from its parent association.

If WASP-10 was ejected recently, then it might be possible to identify its parent cluster. As stars are ejected most likely soon after cluster formation (due to a supernova event in a binary system, e.g. Blaauw 1961 or via dynamical interactions in a dense cluster, e.g. Poveda et al. 1967), the age of WASP-10 should be its kinematic age, i.e. it left its parent cluster some hundred million years ago. For such a long time, it is hardly possible to reconstruct the past trajectory of the system as well as the past trajectory for a potential parent cluster because both, the star and the cluster, have experienced a complete cycle (or even more) around the Galactic centre. Considering a time span up to 1 Gyr, even periodic appearances of close encounters between the star and a cluster could occur. Moreover, it is not unlikely that WASP-10 experienced some perturbations of its path. For those reasons, the parent cluster of WASP-10 might remain unidentified if the star was ejected relatively soon after formation. If, for some reason, WASP-10 was ejected recently, finding its parent cluster could be possible. The system's peculiar spatial velocity is 10 ± 2 km s $^{-1}$ (the heliocentric velocity was corrected for Solar motion and Galactic rotation applying the LSR from Tetzlaff et al. (2010b) and a value of $V_{\odot, rot} = 225$ km s $^{-1}$). Considering a typical cluster radius of a few parsecs, the parent cluster of WASP-10 is well identifiable if the star system was ejected not earlier than some

Table 5. Open clusters for which close encounters with WASP-10 were found some million years in the past. The first column gives the cluster designation, the second and third columns indicate the separation d between WASP-10 and the cluster centre and the radius R of the cluster. Column four states the time τ of the encounter (time before present) and column five quotes the cluster age as given in Dias et al. (2010). d was derived from 3D Gaussian distributions that can explain the slope of the d distribution, see Tetzlaff et al. (2010a).

Cluster	d (pc)	R (pc)	τ (Myr)	age (Myr)
Platais 2	0 ± 6	10	13	400
ASCC 123	0 ± 12	6	11	260

million years ago. During 20 million years, the star travelled about 200 pc. Taking into account the current distance to the Sun of about 100 pc and considering also previous age constraints, we selected open clusters within 300 pc from the Sun having ages between 100 and 800 Myr (corresponding to the ages of the Pleiades and Hyades, respectively) from the Dias et al. (2010) database for open clusters with full kinematics available with the catalogue as well as the Hyades cluster (WEBDA², Merrimod & Paunzen 2010), 14 clusters in total. We calculated the past orbits of WASP-10 and each cluster using the epicycle approximation (Lindblad 1959; Wielen 1982). Then, we performed a Monte-Carlo simulation varying the distance, proper motion and radial velocity within their confidence intervals to account for their uncertainties. The goal was to find close encounters between WASP-10 and any cluster in the past. Two clusters for which close encounters with WASP-10 were found (within three times the cluster radius corresponding to approximately 3σ), are listed in Table 5. The cluster radius, the time of the encounter and the age of the clusters are given. If WASP-10 really originated from either Platais 2 or ASCC 123, the star is about 260 to 400 Myr old, in agreement with our age estimate of 270 ± 80 Myr. It is, of course, more likely that the star is ejected early in the life of a cluster. It is generally not possible to trace WASP-10 backwards reliably for the estimated age of the system.

The young age of the host star may explain the large radius of its planet, WASP-10b. The non-irradiated models by Baraffe et al. (2003), interpolated for such a young $3 M_J$ planet, results in a radius of $\sim 1.2 R_J$. Irradiation may increase the planetary radius by ~ 10 per cent, compared to non-irradiated models (Baraffe et al. 2003). An analogous procedure based on irradiated planetary models by Fortney, Marley & Barnes (2007) and Baraffe, Chabrier & Bartman (2008) also gives a radius of $\sim 1.2 R_J$ for a 300 Myr old giant planet. This estimate is consistent with the radius of WASP-10b reported by Christian et al. (2009), Dittmann et al. (2010) and Krejcová et al. (2010).

7 CONCLUSIONS

Our investigation indicates that transit timing of WASP-10b cannot be explained by a constant period of the exoplanet.

² <http://www.univie.ac.at/webda/webda.html>

The distribution of data points in the $O-C$ diagram reveals the existence of a periodic signal. We constructed a provisional hypothesis assuming the presence of the third body in the system. Combining results of 3-body simulations and RV measurements the most likely explanation of the observations is given by a model with a second planet of mass of $\sim 0.1 M_J$ and orbital period of ~ 5.23 d.

The reanalysis of RV data shows that WASP-10b orbits its active host star in a circular orbit. The signature of stellar rotation was found in RV measurements. This effect was misinterpreted in previous studies as a non-zero eccentricity of the transiting planet. The second planet would generate wobbling of the host star with the semi-amplitude of $\sim 14 \text{ m s}^{-1}$ – much less than the RV variation caused by the stellar rotation. Although we managed to distill this weak signal, we emphasize that further simultaneous spectroscopic and photometric observations are needed to study the activity of WASP-10 and verify the existence of the planet WASP-10c.

WASP-10 was found to be a relatively young star. Assuming that this finding, which is based on the stellar gyrochronology, is correct, then the observed radius of WASP-10b is consistent with theoretical models and no tidal heating is required to match its radius. If planetary gas giants form by gravitational contraction, then young planets should be larger than older ones. If the planets of WASP-10 formed at larger separation than their present location, then migration must have taken place within the young age of the star.

The existence of WASP-10c could be independently confirmed if it is a transiter. Assuming that its radius is $\sim 0.4 R_J$, i.e. similar to exoplanets of the similar mass like HAT-P-11b (Bakos et al. 2010) or Kepler-4b (Borucki et al. 2010), the expected flux drop during a transit would be ~ 0.3 per cent or even greater if we consider the young age of the system. This could be observable with a large ground-based telescope.

In the proposed model the ratio of orbital periods of the planets $P_c/P_b = 1.69$ is very close to 5:3 orbital resonance. A significant fraction of known multi-planet systems are in MMRs, mainly in low-order ones. Two planets in wide orbits and trapped in a 3:2 MMR were found around HD 45364 by RV measurements (Correia et al. 2009). Planets in the 4-planetary system around GJ 581 (Mayor et al. 2009) are very close to 5:2 (GJ 581b and c) and 5:3 (GJ 581e and b) MMRs (Papaloizou & Terquem 2010). Therefore, we conclude that the architecture of the WASP-10 system would not be completely unusual.

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